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REPORT DOCUMENTATION PAGE			OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 2/17/97	3. REPORT TYPE AND DATES COVERED Final Technical Report: 5/1/94-2/28/97	
4. TITLE AND SUBTITLE Spatial Frameworks for Perceived Environments		5. FUNDING NUMBERS G: F49620-95-1-0404 61103D 3484/Y5	
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office Of Scientific Research/A 110 Duncan Ave., Suite B115 Bolling AFB, DC 20332 <i>Dr. Haddad</i>		10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES		19970616 132	
12a. DISTRIBUTION STATEMENT (If distribution is limited, state the distribution statement used) Unlimited		12b. DISTRIBUTION CODE 2	
13. ABSTRACT (Maximum 200 words) Research examined mental representation of spatial information. Spatial frameworks are based on an egocentric reference frame, and intrinsic computation on an object-centered frame. Research documented the use of spatial frameworks in memory for observed and modelled scenes, but intrinsic computation for memory of diagrams. Intrinsic computation was also used in perception of models and diagrams. Reference frame is under strategic control - instructions can alter the representation of diagrams and models. Spontaneous use of spatial frameworks is determined by the directness with which information about all three spatial dimensions is conveyed. Related experiments revealed that differences in accessibility result from the relative salience of body axes. Laterality and handedness do not affect the accessibility of spatial locations. Additional research documented the use of a Euclidean metric for representing haptically explored space and the effortful rather than automatic rehearsal of visual spatial location. The rehearsal process depends critically on eye movements between locations. New projects have begun to explore pattern perception and the metric structure underlying spatial concepts.			
14. SUBJECT TERMS spatial frameworks, spatial cognition, mental models, memory, perception, geometry, concepts, laterality, diagrams		15. NUMBER OF PAGES 44	
17. SECURITY CLASSIFICATION OF REPORT Unclassified		16. PRICE CODE	
18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT UL	

## **Abstract**

Research examined mental representation of spatial information. Spatial frameworks are based on an egocentric reference frame, and intrinsic computation on an object-centered frame. Research documented the use of spatial frameworks in memory for observed and modelled scenes, but intrinsic computation for memory of diagrams. Intrinsic computation was also used in perception of models and diagrams. Reference frame is under strategic control - instructions to use one or the other guides the representation of diagrams and models. Spontaneous use of spatial frameworks is determined by the directness with which information about all three spatial dimensions are conveyed. Related experiments revealed that differences in accessibility result from the relative salience of body axes. Laterality and handedness do not affect the accessibility of spatial locations. Additional research documented the use of a Euclidean metric for representing haptically explored space and the effortful rather than automatic rehearsal of visual spatial location. The rehearsal process depends critically on eye movements between locations. New projects have begun to explore pattern perception and the metric structure underlying spatial concepts.

F49620-95-1-0404  
AFOSR Grant No. ~~94-0220~~  
Spatial Frameworks for Perceived Environments

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February 17, 1996  
Period Covered: May 1, 1994 to February 28, 1997

**FINAL TECHNICAL REPORT**

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## Background

Our research has investigated the nature of spatial representation. Much of the work completed has focussed on the frames of reference used to define directions and other spatial relations. Three frames of reference are used to describe space: the egocentric or viewer-centered frame, the object-centered frame, and the environment-centered frame. The frame of reference establishes a correspondence between the mental representation of space and the physical or perceived space.

The understanding of direction in a frame is guided by the geometry of space, but also by the physical nature of our terrestrial environment, by the structure of the human body, and potentially by functional demands of operating in space. Research has indicated that people create mental models to represent these aspects of the spatial situation (e.g., Glenberg, Meyer & Lindem, 1987; Johnson-Laird, 1983; Morrow, Greenspan & Bower, 1987). A mental model is a representation of the underlying situation as it is perceived is organized around salient features of that situation. Mental models preserve physical properties of space such as relative position, and relative distance. Furthermore, spatial features determine the accessibility of information from mental models.

### *Memory and Perception of a Simple Spatial Situation*

The current research has focussed on one prototypic spatial situation, that of a person surrounded by objects. We considered one person (the subject) looking at another person who was surrounded by objects to his/her six body sides (front, back, head, feet, left, and right).

A schematic diagram of this situation is shown in Figure 1. The person is in a scene, perhaps standing on a table or stepladder in her workshop. This situation is prototypic of many spatial situations involving people, objects, and layouts that must be communicated between people. The diagonal line depicts depth in the scene. Six objects are located around her, all directly aligned with a major body side. Although simple, this situation has ecological validity as well as being tractable. Most of the time, people find themselves in environments with objects located more or less to the sides of their bodies.

The same basic task was employed in all experiments. Subjects first studied a scene presented in a diagram or a 3D model. The person in the scene then rotated to face another object and/or changed posture (e.g., from upright to reclining). Subjects were presented with direction probes - terms referring to the person's six body sides - and they named the object currently at that direction relative to the person. Probes were answered either from memory or while viewing the scene. Because certain body axes have a favored status in our interactions with the world, they are more salient to thinking about spatial relations. These differences lead to differences in retrieval times for spatial relations and indicate the spatial concepts organizing memory or perception.

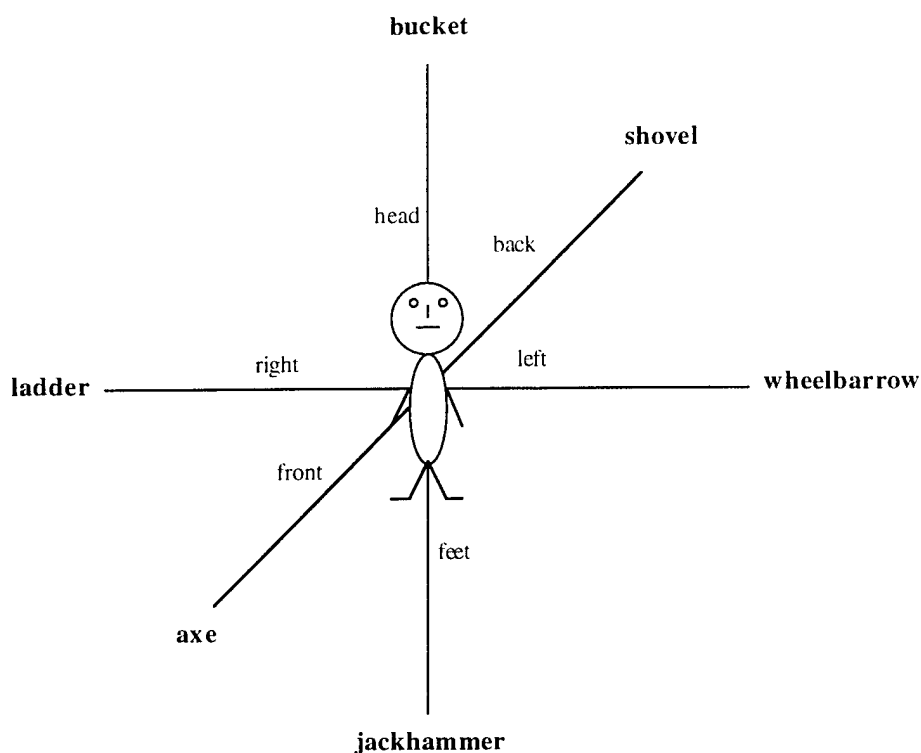


Figure 1. Diagram of the prototypic scene. A person is surrounded by objects to his or her six body sides. This is also an example of a diagram used to study memory of diagrammed scenes.

## Two Alternative Frameworks

Several hypotheses regarding subjects' mental representations and performance can be proposed. The equiavailability model, for example, predicts equal access to all spatial relations (see Levine, Jankovic, & Palij, 1982), whereas the mental transformation model predicts subjects use mental rotation to identify objects so that response time depends on the degrees of rotation necessary (see Franklin & Tversky, 1990). Neither of these hypotheses, however, was supported by the data in any experiment reported here. Thus, we concentrated on two main alternatives.

### *Spatial Framework Analysis.*

Franklin and Tversky (1990) originally devised the spatial framework analysis to describe mental models readers derive from narratives. According to this theory, subjects construct a mental spatial framework consisting of extensions of the three body axes, head/feet, front/back, and left/right, and associate objects to that framework. The accessibility of an axis depends on characteristics of the body and the perceptual world. For an upright observer, the head/feet axis is most accessible because it is physically asymmetric and correlated with the fixed environmental axis of gravity. The front/back axis is next most accessible. It is not associated with a fixed environmental axis but is strongly asymmetric, separating the world that can be seen and manipulated from the world that cannot be easily perceived or manipulated. The left/right axis is

least accessible because it has no salient asymmetries. For the upright observer, the spatial framework analysis predicts that people should be fastest to identify objects at the head or feet, followed by front or back, followed by left or right. In addition, because perceptual and behavioral asymmetries so strongly favor front over back, people should be faster to front than back.

The situation changes for a reclining person. The head/feet axis is no longer correlated with gravity, so the accessibility of axes depends solely on their asymmetries. The perceptual and behavioral asymmetries of the front/back axis are stronger than those of the head/feet axis. The left/right axis has the weakest asymmetries. Thus, for a reclining person, identification along front/back should be faster than head/feet, which should be faster than left/right.

Another case explored in some experiments is the upsidedown orientation. Here, the head/feet axis is aligned with gravity as for the upright case, but in a non-canonical orientation. The asymmetries of front/back could render this axis most salient, as for the reclining posture. In the paradigm used, however, the character rotates around the head/feet axis. Having the axis of rotation aligned with gravity should render it more salient than front/back. The prediction for an upsidedown character is the same as for an upright one, with access fastest to head/feet, followed by front/back, followed by left/right. Subjects, however, should be slower overall due to the character's non-canonical orientation.

The spatial framework analysis applies to the situation studied here when the subject adopts the internal perspective of the character. In this case, response times to identify objects at probed directions around the character would conform to the spatial framework pattern because the subject "mentally" occupies the position of the person in the scene. The crucial factor is that spatial frameworks are based on an egocentric frame of reference.

#### *Intrinsic Computation Analysis.*

According to the intrinsic computation analysis, observers apply an object-centered reference frame and identify the intrinsic sides of the person by using the same general perceptual mechanisms used in object recognition. Object recognition involves extracting the axes of the object because identification depends critically on how features are spatially related to one another. Some intrinsic axes of objects are more readily determined than others. Many researchers have demonstrated that the top/bottom axis (the head/feet in humans) is primary in object perception and the first axis abstracted during object recognition (Jolicoeur 1985; Maki 1986; Rock, 1973). People are faster to identify the top/bottom (head/feet) than the front/back (Jolicoeur, Ingleton, Bartram, & Booth, 1993) and the left/right (Corballis & Cullen, 1986) of objects at all orientations (including reclining). The left/right axis is derived from knowing the top or bottom and front or back sides of an object and is necessarily slowest. On this basis, the main prediction of the intrinsic computation analysis is that an observer will *always* be fastest to identify objects at the head/feet, then the front/back, and finally the left/right of a viewed person, regardless of the person's posture. Thus, the main way to distinguish the use of spatial frameworks from intrinsic computation is to compare patterns of response times for head/feet and front/back across upright and reclining orientations.

Intrinsic computation makes use of general perceptual processes specialized for the kind of task we have examined - determining directions within an object-centered frame of reference. Also, it allows an observer to identify directions without mentally placing themselves in another

person's perspective or creating a mental spatial framework. This eliminates any conflict between the subject's actual viewpoint and a spatial framework from the other person's perspective.

### Observed Scenes.

Research in the literature (e.g., Franklin & Tversky, 1990; Glenberg et al, 1987; Morrow, et al., 1987) has typically dealt with narrative comprehension. This, however, only one way of expressing spatial knowledge. Initial research focussed on the relation between learning scenes from narratives and from visual observation. In reading a narrative, one must entirely construct the spatial configuration. This may place a strong impetus on the reader to employ spatial frameworks. When observing a scene, this is not the case and other factors may influence the mental frame of reference used.

Thus, we (Bryant, Tversky, & Lanca, 1997) posed the question of whether mental models established from narrative are equivalent to mental models established from observation. To answer it, we had subjects visually learn spatial arrays around themselves and compared the pattern of response times for responding from memory to the pattern obtained previously for learning scenes from narrative. A second question was whether spatial mental models are like internalized perception. To answer it, we compared the patterns of response times for responding from memory of internal scenes to the pattern obtained when responding from perception. In the first experiment, subjects learned a physical spatial array of objects. Subjects stood or reclined on a bench in an empty room. Large pictures of objects were hung on the walls, ceiling, and floor at the six directions from the subject's body. After learning the scene, subjects responded to direction probes either from memory or while looking at the scene.

In memory for observed scenes, subjects produced the pattern of response times associated with the spatial framework analysis, as illustrated in Table 1. The fact that the pattern of response times from memory of an observed scene is the same as the pattern of response times from memory of a described scene supports the conclusion that spatial frameworks constructed from descriptions are equivalent to those constructed from experience.

Table 1  
Mean Response Times (in Seconds) in Memory for Observed Scenes (Adapted from Bryant et al., 1997; Experiment 1)

Posture	Direction					
	Head	Feet	Front	Back	Left	Right
Upright	1.14	1.14	1.18	1.29	1.48	1.46
Pairwise means	1.14		1.24		1.47	
Reclining	1.32	1.35	1.26	1.31	1.52	1.46
Pairwise means	1.34		1.28		1.49	

A different pattern emerged in the perception condition. Here, subjects had the opportunity to look in probed directions, which they often did. Subjects, however, also responded without

looking on numerous trials. Thus there were two observed patterns of data. When subjects did not turn to look when responding, their response times conformed to the spatial framework analysis and reflects memory for the scene. When subjects actually did look at the probed direction to find the object, response times exhibited a *physical transformation* pattern. Specifically, times to front were be fastest, times to back slowest, and times to the other four directions, all 90 degrees from front, were be in between. Thus, the more degrees of rotation necessary, the longer it took to respond. The perception condition offered the first indication that the spatial framework analysis is not a universal description of the way people deal with space around themselves.

### Representation of Depictions of Space

Space can be depicted in a number of ways. Previous research, for example, has examined verbal descriptions of scenes (Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990). Two common kinds of depictions are 3D physical models and 2D diagrams. Each has its own unique features and could potentially be processed differently.

One issue addressed by our research was whether diagrams and models induce or favor different mental representations. Subjects have been found to create spatial frameworks for memory of models, but use intrinsic computation during perception (Bryant et al., 1997; Experiment 3). At issue is whether these findings reflect anything specific to 3D models. The use of diagrams is an interesting case because a diagram is intermediate to language and physical environments. A diagram is representational, intended to convey spatial information about a place that is not physically present, but also a spatial medium having its own spatial properties. The study of diagrams has ecological justification in that maps, sketches, and pictures are commonly used to provide spatial information.

A second question was whether the spatial framework and intrinsic computation analyses reflect different processes for expressing spatial knowledge in memory versus perception. Research (Bryant et al., 1992, 1997; Franklin & Tversky, 1992) has found that subjects employ spatial frameworks in memory for narratives and observed scenes. This suggested that regardless of how a person learned a spatial configuration, he or she created a mental model of the situation. The representative nature of diagrams strengthens this intuition because a diagram, to some extent, *describes* a scene. As such, it calls for a situational model.

In contrast, intrinsic computation has been observed in perception of observed scenes. Because the viewer is looking at the scene, it might be very difficult, or even impossible, to ignore one's own perspective. Intrinsic computation also capitalizes on perceptual processes to identify the sides of the person, then scan in the appropriate direction - a natural and direct way to locate objects.

Although perception of physical scenes invokes intrinsic computation, a diagram is unlike a real scene in several important respects. A diagram is two-dimensional and depth must be inferred by cues such as linear perspective. Diagrams can be held vertically, but are often viewed flat so that neither of its two dimensions is aligned with gravity (i.e., a diagram has no fixed relation to gravity). The top of a diagram can also be rotated with respect to the viewer, so that the diagram's vertical does not correspond to the viewer's intrinsic vertical (i.e., a diagram has no fixed relation to the observer). These factors may make diagrams so abstract that a viewer would prefer to construct a spatial framework even in perception.



### *Model scenes*

In one experiment, subjects viewed a 3D model of a scene containing a doll surrounded by drawings of objects beyond the doll's head, feet, front, back, left, and right. One group of subjects participated in a memory condition. After subjects studied the model, it was removed from view and subjects responded to direction probes for objects from the doll's perspective from memory. During the procedure, subjects were periodically told that the doll had rotated to face a new object, or had changed posture, so that they needed to update the current positions of objects relative to the doll to respond to direction probes. We expected that subjects would construct spatial frameworks from the doll's point of view to keep track of the directions of objects relative to the doll. A second group of subjects participated in the perception condition and responded to direction probes while observing the model scene. The doll was physically rotated and reclined in the model. The drawback of using a spatial framework here is that the doll's perspective conflicts with the subject's own perspective. Using intrinsic computation to report objects in this condition would eliminate the conflict between the subject's and doll's perspective.

The results of this experiment, shown in Table 2, are quite clear. When subjects responded from memory, response times conformed to the spatial framework pattern. Critically, front/back was faster than head/feet for reclining dolls. This suggests that subjects mentally adopt the person's perspective and construct an egocentric spatial framework. When subjects responded from perception, while actually viewing the model scene, subjects were faster to head/feet, followed by front/back, followed by left/right for *both* upright and reclining postures. This indicates that subjects used an object-centered frame.

Table 2  
Mean Response Times (in Seconds) for Upright and Reclining Doll in Memory and Perception

Posture	Direction					
	Head	Feet	Front	Back	Left	Right
<b>RESPOND FROM MEMORY</b>						
Upright	1.80	1.84	2.02	2.27	2.67	2.73
Mean	1.82		2.15		2.70	
Reclining	2.58	2.60	2.28	2.31	3.13	3.24
Mean	2.59		2.29		3.18	
<b>RESPOND FROM PERCEPTION</b>						
Upright	1.01	1.00	1.07	1.08	1.25	1.28
Mean	1.00		1.08		1.26	
Reclining	1.12	1.12	1.20	1.21	1.36	1.39
Mean	1.12		1.20		1.38	

A second experiment replicated and extended the memory condition of the previous

experiment. Rather than have the person in the scene adopt only an upright or reclining posture, the person was "rotated" in the picture plane so that he/she was upright, reclining with the head to the left, upside down, and reclining with the head to the right. Subjects learned scenes and were tested using the same procedure as before.

The results are shown in Table 3. There were significant effects of direction and orientation and their interaction, indicating that subjects exhibited overall slower and qualitatively different patterns of response times when the person was not upright. The results indicate that subjects create spatial frameworks to remember 3D model scenes. Subjects were faster to head/feet than front/back when the person was aligned with gravity in the upright and upsidedown postures, but faster to front/back than head/feet when the person was in the reclining postures. This replicates the finding of Bryant et al. (1997; Experiment 3) and extends it to the upsidedown posture.

Table 3  
Mean response times (in seconds) for memory of models with a person at four orientations

Orientation	Direction					
	Head	Feet	Front	Back	Left	Right
Upright	3.474	3.438	3.847	4.041	4.162	4.627
Mean	3.456		3.944		4.394	
Upsidedown	3.845	3.965	4.541	4.494	6.424	5.558
Mean	3.905		4.518		5.991	
Reclining to left	4.249	4.346	3.806	3.765	5.001	4.866
Mean	4.298		3.786		4.934	
Reclining to right	4.225	4.296	3.797	3.745	4.603	4.681
Mean	4.260		3.771		4.642	

Overall, the results of the two experiments suggest that, for this kind of scene, subjects employ spatial frameworks to remember locations of objects. To do so, subjects mentally adopt the perspective of the person they have viewed in the scene and impute the egocentric properties of their own perspective onto that person. Thus, factors that determine how we experience space affect how we remember space around another person.

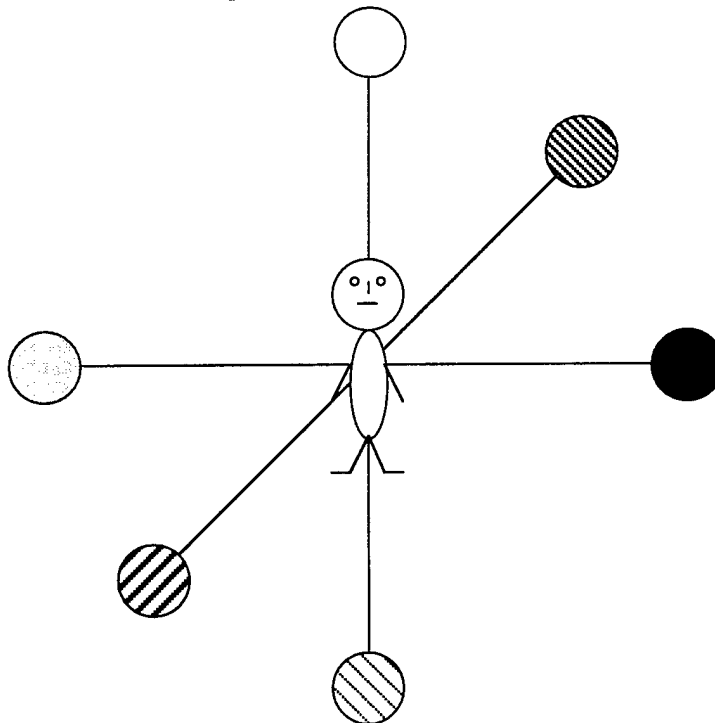
#### *Mental Frames in Perception of Diagrams*

Another way of dealing with space is by use of diagrams. This is an interesting case because a diagram is intermediate to language and physical environments. A diagram is representational, intended to convey spatial information about a place that is not physically present, just as language.

A diagram, however, is also a physical thing and a spatial medium having its own spatial properties, just as real environments. The study of diagrams has ecological justification in that maps, sketches, and pictures are commonly used to provide spatial information. It will also allow us to determine what sort of mental framework is used to understand depictions of space. At issue is whether, when people view a diagram of a spatial configuration, they use the spatial concepts associated with language and memory or whether they use the spatial processes associated with perception.

In recent studies (Bryant, in press), we considered perception of diagrams depicting a person surrounded by objects to all sides - a pictorial analog of the narratives and physical models studied before. An example is shown in Figure 2. To avoid potential confounds of object identifiability, these diagrams used colored circles as targets and subjects named the color in response to direction probes.

The following experiments employed a common general paradigm. Subjects viewed a series of diagrams depicting a person inside a three-dimensional array of colored circles. In all cases, the diagrams contained a schematic human figure at the center. Vertical and horizontal lines depicted those dimensions, and, in all cases, a diagonal line represented depth. The configuration of colors around the person was random from trial to trial. The person was shown in one of four orientations, and within each orientation was rotated around its head/feet axis, so that orientation and facing were unpredictable from trial to trial. The subjects' task was to indicate the color of a circle at a cued direction relative to the person's perspective; i.e. to the person's left, front, head, etc. The measure of interest was response time to correctly name the color.



*Figure 2.* Figures used by Bryant (in press). In the experimental materials, each circle was presented in a unique color (blue, red, yellow, green, pink, or black).

The first goal was to demonstrate the use of some mental frame to locate objects in a diagram.

From this, we must also delineate the conditions under which such a mental frame is used. Logan (1995) has proposed that a frame of reference is applied in perception whenever a spatial relation between one object (a cue) and another object (a target) must be computed to perform a task (e.g., when directing attention from one object to another). Tasks that do not require computing a mental frame include those in which subjects can respond only to the cue or target objects and tasks in which subjects can switch attention between the two before responding. Thus, if a subject is asked to name an object at a particular direction around a person or object, the subject must compute a mental frame to define spatial relations and use the frame to direct attention. In contrast, if a subject is asked simply to orient to and identify objects in a display, no mental frame is necessary because the spatial relations among objects are irrelevant to the task. Logan (1995) has demonstrated that people employ mental frames to direct attention in specified directions from a cue to a target in two-dimensional displays. He also found that mental frames are not employed in tasks requiring subjects simply to orient to objects or locations.

Three experiments extended Logan's (in press) findings to diagrams depicting three-dimensional (3D) scenes. The first experiment contrasted two conditions in the general paradigm. In one condition, subjects received verbal probes naming a direction referring to one of the person's six body sides and responded by naming the color of the circle in that direction from the person. This task should require subjects to impose a mental frame on the diagram because the subject must identify a spatial relation in order to locate the appropriate circle. In a second condition, subjects received circle probes that highlighted one of the colored circles surrounding the person. Subjects responded by naming that color. This task should not induce a mental frame because the subject need only orient to the highlighted circle to report its color.

The results are shown in Table 4. Consistent with predictions, subjects employed a mental frame to identify objects in response to verbal direction probes. This is indicated by the finding that subjects were fastest to head/feet, followed by front/back, followed by left/right. The circle probes did not require subjects to compute spatial relations. Here, subjects responded equally fast to all directions, indicating that subjects did not use a mental frame.

Table 4  
Mean Response Times (in seconds) to Name Color to Verbal and Circle Probes (From Bryant & Tversky, 1995; Experiment 1)

Probe Type.	Direction					
	Head	Feet	Front	Back	Left	Right
Verbal	1.469	1.417	1.792	1.888	2.488	2.480
Mean	1.443		1.840		2.484	
Circle	0.923	0.920	0.911	0.901	0.913	0.906
Mean	0.922		0.911		0.910	

A second experiment replicated the finding that differential access depends on interpreting

some directional probe, but also determined whether the probe must be a verbal direction name. It has been suggested that the advantage in processing directions such as above and below relative to left and right results from differences in processing the verbal direction terms, not from any difference in conceiving of those spatial relations (Maki, Grandy, & Hauge, 1979). Other research, however, has indicated that the effect is not the result of verbal labelling (Farrell, 1979; Maki, 1979; Maki & Braine, 1985). The same general procedure was used, but subjects' task was to indicate the direction of a probed item rather than the identity of an item in a probed direction. When a circle probe was presented around a colored dot, subjects responded with the direction of the color relative to the person in the diagram. This response requires a mental frame even though detecting the probe and object does not. The verbal probes consisted of the names of colors and subjects responded by indicating its direction.

Subjects were faster to head/feet than front/back than left/right for *both* verbal and circle probes. Thus, mental frames were used to respond to both types of probes. This effect does not depend on probing subjects with verbal direction labels, but occurs when subjects must make a judgment of relative direction.

A third experiment provided another demonstration that viewers apply a mental frame to interpret directions in diagrams. Here, non-verbal arrow probes were used. For each diagram, an arrow appeared pointing along one of the six body directions of the person in the diagram. In one condition, subjects indicated the direction, relative to the person, in which the arrow was pointing. In a second condition, subjects named the color of the circle at the direction in which the arrow probe pointed. Subjects should apply a mental frame in the first condition because they must identify a spatial relation. Subjects may apply a mental frame in the second condition if they treat the arrows as symbols for direction categories. Farrell (1979), Maki and Braine (1985), and others have found that subjects are faster to discriminate up/down from left/right in 2D displays when subjects respond to arbitrary letters that stand for directions. Arrows are commonly used to refer to directions and these probes may act like symbolic verbal direction terms. If so, subjects will need a mental frame to interpret the probes. Alternatively, subjects may simply view the arrows as directional cues because there is no need to interpret the arrow in relation the person in order to solve the task. This is an example of a task that Logan (in press) describes as solvable by shifting attention from cue to target.

The results of the direction naming task replicated earlier experiments: subjects were faster to head/feet than front/back than left/right, indicating the use of a mental frame. Response times were equal to all directions in the color naming task. Thus, subjects did not impose a mental frame in this case. It appears they did not treat arrow probes as symbols standing for direction categories. Instead, they simply used them to direct attention to the appropriate location in the diagram.

*Conclusions.* The results of three experiments indicate that subjects did employ a 3-D mental frame to identify directions. The mental frame appears to be a coherent 3-D representation of directions around the person, despite the fact that the diagram itself was 2-D. A simple diagonal line depicted relations in depth. The line was by no means an overpowering depth cue. Subjects, however, generally responded to direction probes along the diagonal in the same fashion as directions along the other two dimensions. That is, the diagonal did not affect the pattern of response times in experiments, although it did affect overall response times. Subjects tended to be somewhat slower to any direction associated with the diagonal compared to the same direction associated with the vertical or horizontal. Thus, it took more effort to incorporate depth, which was depicted by a diagonal, into the mental frame than axes that directly corresponded to spatial

axes in the environment. The diagonal, however, did not seem to fundamentally change the way relations were computed.

A second purpose of the experiments was to verify that a mental frame is imposed on diagrams only when subjects must identify a spatial relation. Logan (1995) has argued that a mental frame is a cognitive structure used to extract directions in perceived displays and require effort to create. Tasks that could be performed simply by orienting to locations or shifting attention to cues to name colors did not induce a mental frame. Thus mental frames are cognitive strategies for analysing spatial relations in observed scenes.

*Qualifier.* The use of mental frames from the *external* perspective was investigated for observed physical scenes and diagrammed scenes (Bryant, Lanca, & Tversky, 1995). Subjects used a mental frame for the physical scenes. They were fastest to identify objects in above/below, followed by front/behind, followed by left/right relations, which is consistent with the external spatial framework analysis. For diagrams, however, subjects were not faster to above/below than left/right, implying that they were not using a mental frame. Thus, the use of mental frames to compute spatial relations in diagrams may be restricted to the relatively more difficult case of the internal perspective of another person and not to one's own perspective.

Table 5  
 Mean Response Times (in seconds) to Name Color for a Person in Four Orientations

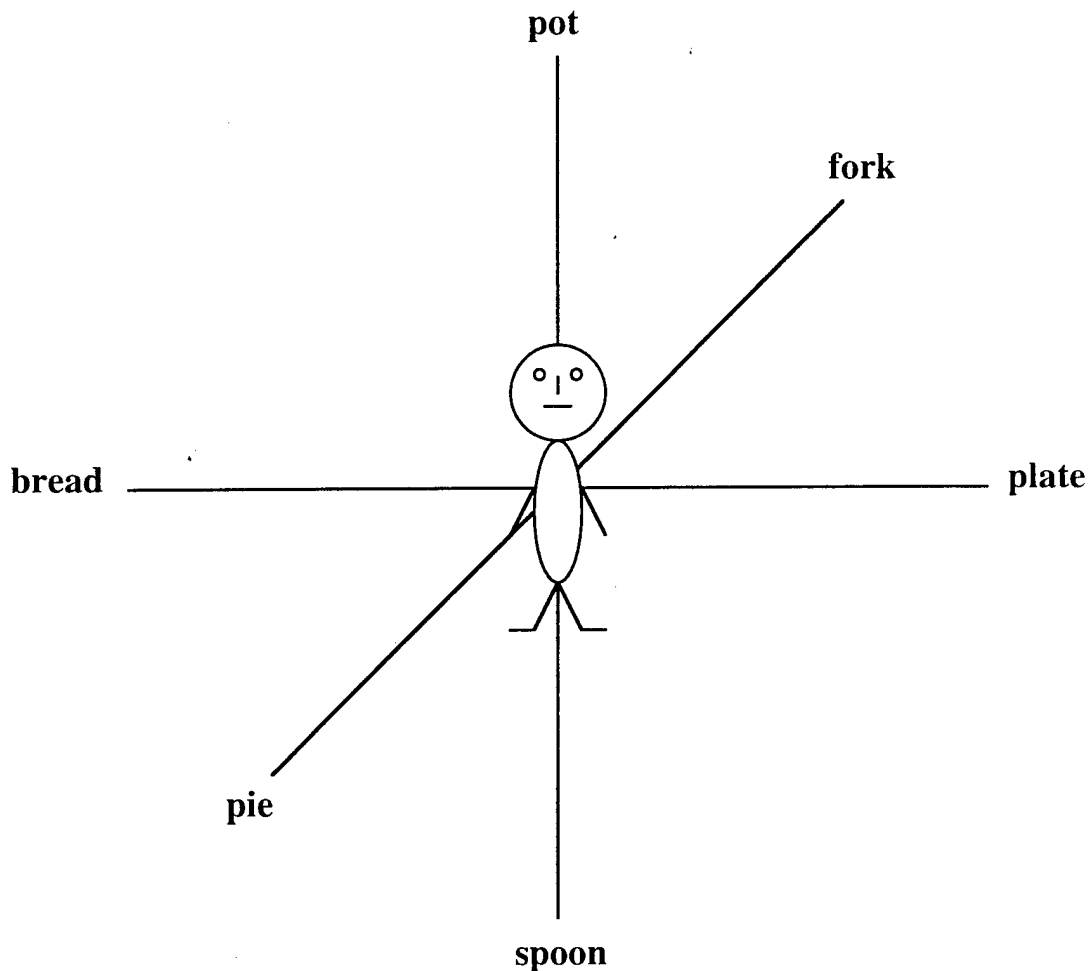
Orientation	Direction					
	Head	Feet	Front	Back	Left	Right
Upright	1.209	1.272	1.643	1.602	2.256	2.159
Pairwise means	1.240		1.622		2.208	
Upside down	1.260	1.291	1.873	1.825	3.165	3.408
Pairwise means	1.276		1.849		3.286	
Reclining to left	1.274	1.312	1.864	1.801	2.318	2.315
Pairwise means	1.293		1.832		2.316	
Reclining to right	1.334	1.285	1.861	1.782	2.494	2.430
Pairwise means	1.310		1.822		2.462	

#### *Mental Frames for Diagrammed Scenes in Perception and Memory*

One experiment distinguished between the spatial framework and intrinsic computation analyses for diagrammed scenes. Subjects viewed a series of 288 diagrams like that in Figure 2. The orientation of the figure was varied within-subject so that the person was upright, reclining to the left, reclining to the right, and upsidedown on an equal number of trials. The person appeared

in any one of four rotations around the head/feet axis. The order of diagrams was random and so the orientation of the person was unpredictable. Subjects received a direction probe for each diagram and named the color at that direction. The results shown in Table 5 are clear. At all orientations, subjects were faster to head/feet than front/back than left/right. Thus subjects employed intrinsic computation in perception of diagrams. Even though the drawings were highly representational, they tapped the same perceptual spatial concepts that guide the locating of objects in observed 3D physical scenes.

### **Bob in the Kitchen**



*Figure 3.* Example of a diagram used to convey scenes in experiments examining memory for diagrammed scenes.

An experiment examined memory for scenes depicted in diagrams, again contrasting the spatial framework and intrinsic computation analyses. Subjects studied diagrams like that in Figure 3, learning the positions of objects around a person in a particular scene. They then put the diagram aside and responded to direction probes on a computer. The computer would occasionally

inform the subject that the person had turned or changed orientation, and presented direction probes as in previous studies. The person was oriented in upright, reclining to the left, reclining to the right, or upsidedown postures. Response times to direction probes conformed to predictions of the intrinsic computation analysis; i.e., they were faster to head/feet than front/back at *all* orientations of the person (see Table 6).

Subjects employed intrinsic computation in perception of 3D model scenes, but spatial frameworks for memory of models. The similarity of results for memory and perception of diagrams contrast with the results for modelled scenes.

Table 6  
Mean Response Times (in seconds) for Memory of Diagrams with a Person at Four Orientations

Orientation	Direction					
	Head	Feet	Front	Back	Left	Right
Upright	3.441	3.366	3.778	3.935	4.687	4.568
Mean	3.404		3.856		4.628	
Upside down	3.799	3.800	4.063	4.346	6.253	6.051
Mean	3.800		4.204		6.152	
Reclining to left	3.936	4.024	4.116	4.355	4.786	4.799
Mean	3.980		4.232		4.792	
Reclining to right	3.994	4.086	4.089	4.106	4.820	4.666
Mean	4.040		4.098		4.743	

### *Strategic Effects*

People responded differently in memory for models and diagrams, which reflects the adoption of two different frames of reference. The *internal* frame of reference involves mentally adopting the perspective of the person in the scene. One's mental model is based on the concepts related to one's own experience in space; i.e., a spatial framework. The *external* frame of reference is the perspective outside the scene that one has as a viewer. Here, one's representation is based on the concepts related to perception of the depiction of the spatial array; i.e., intrinsic computation.

What predicts whether a subject will adopt the internal or external frame of reference? Schwartz (1995) has suggested that the fidelity of depictions predicts how people will reason about them. In the experiments here, the model is more perceptually faithful to a real scene than the diagram. It is possible that this made it easier for subjects to form mental models of the scenes depicted in models than those in diagrams. The diagrams presented obstacles to adopting the internal perspective. They were highly schematic and required effort to infer depth and build a 3D



representation, and the diagrams referred to another person.

If the frame of reference, rather than the kind of depiction per se, determines the nature of one's mental model of a depicted scene, people should be able to alter how they represent scenes in our paradigm. Both models and diagrams are depictions of scenes and it is possible that a viewer could form a mental model of a diagram and treat a physical model as an object. Two experiments tested this possibility. In both, subjects were given special instructions concerning the perspective to adopt on scenes. The goal was to determine whether the kind of mental representation created in memory is under strategic control.

Table 7

Mean response times (in seconds) for memory of diagrams with a person at four orientations with subjects instructed to adopt internal perspective

Orientation	Direction					
	Head	Feet	Front	Back	Left	Right
Upright	3.575	3.521	3.735	3.974	4.063	4.169
Mean	3.548		3.854		4.116	
Upside down	3.867	3.759	4.131	4.306	5.049	5.124
Mean	3.813		4.218		5.086	
Reclining to left	4.182	4.246	3.934	3.903	4.585	4.620
Mean	4.214		3.918		4.60	
Reclining to right	4.108	3.952	3.871	3.860	4.345	4.253
Mean	4.030		3.866		4.299	

In the first experiment, subjects viewed diagrams that referred to themselves in a scene and were explicitly told to create a mental model of themselves in the scene. The diagrams from previous experiments were used. The only difference was that subjects were told that the diagrams referred to themselves. The procedure was the same as well, except that subjects were told to imagine what the scene would be like with themselves inside it. These changes were intended to encourage subjects to adopt an internal perspective. The results are presented in Table 7. The pattern of response times conforms to the predictions of the spatial framework analysis. Critically, subjects were faster to head/feet than front/back for the upright and upsidedown orientations, but faster to front/back than head/feet for the reclining orientations. Instructions to adopt an internal perspective radically altered the pattern of response times. People are not limited to representing diagrams in an external perspective by using intrinsic computation.

Table 8

Mean response times (in seconds) for memory of model scenes with a person at four orientations with subjects instructed to adopt external perspective

Orientation	Direction					
	Head	Feet	Front	Back	Left	Right
Upright	3.435	3.349	3.643	3.813	4.223	4.026
Mean	3.392		3.728		4.124	
Upside down	3.737	3.639	4.076	4.221	4.935	5.047
Mean	3.688		4.148		4.991	
Reclining to left	3.738	3.704	4.051	4.006	4.700	4.428
Mean	3.721		4.028		4.564	
Reclining to right	3.604	3.589	3.758	3.856	4.361	4.307
Mean	3.596		3.807		4.334	

The next experiment determined whether subjects could be induced to employ intrinsic computation for model scenes. In this experiment, subjects viewed 3D model scenes containing a person surrounded by objects. Subjects, however, were specifically instructed to mentally represent the model from an external perspective by forming a visual image of what the model looked like from their vantage point. They were also told to update this image every time they were told the person changed orientation in the scene. These instructions were intended to induce subjects to treat the model as an object in relation to themselves.

The results shown in Table 8 indicate that subjects employed intrinsic computation. At all orientations, subjects were faster to head/feet than front/back. This finding contrasts to the spatial framework pattern observed in memory for models when subjects were not given special instructions. Instructions to treat diagrams as real scenes and to adopt the internal perspective led subjects to employ spatial frameworks in memory of diagrams. Likewise, instructions to treat model scenes as depictions and to adopt the external perspective led subjects to use intrinsic computation in memory of models. Thus, both analyses can apply to memory of modelled and diagrammed scenes. The use of one or the other is a strategic factor, depending on how the viewer mentally treats the depiction of the spatial array. This finding indicates that the kind of depiction (diagram or model) does not control the nature of a viewer's mental representation.

*Conclusions.* Subjects used intrinsic computation for perception of models and diagrams, but spatial frameworks for memory of models (Bryant et al., 1997) and narratives (Bryant et al., 1992; Franklin & Tversky, 1990). Initially, it appeared that there was a difference in the kinds of spatial concepts and processes invoked in memory versus perception of space. The current results indicate that there is no straightforward respond-from-memory versus respond-from-perception

dichotomy determining the analysis people apply. Subjects spontaneously used intrinsic computation for memory of diagrammed scenes. It was further found that, with special instructions, subjects can be induced to use either intrinsic computation or spatial frameworks for memory of both diagrams and models. Thus, intrinsic computation is not limited to perception, but is a viable strategy for memory. The dichotomy is, instead, between internal and external perspectives or frames of reference. The use of one or the other to define spatial relations determines the kind of analysis used, and hence the pattern of response times to direction probes.

Although the frame of reference determines the kind of analysis, there seems to be a strong tendency to use intrinsic computation in perception. There are several reasons why intrinsic computation analysis should be preferred when subjects locate objects during perception. First perceptual processes seem to be qualitatively different than spatial mental models. Second, intrinsic computation entails only one perspective, that of the observer. If subjects were to have created spatial frameworks of diagrammed scenes, they would have had to coordinate their own viewpoint with that of the person (to whom the probes referred). Maintaining multiple perspectives in mental models causes conflict and increases processing effort, and also seems to disrupt one's ability to create and maintain a spatial framework (Franklin, Tversky, & Coon, 1992). Thus, it is probably very hard, if not impossible, to create a spatial framework of a scene while actually viewing it. The external frame of reference matches the perspective of the observer and requires no additional effort to compute. Finally, taking the perspective of the person in the diagram logically implies that the observer has already determined the body sides of the person. To align one's head, front, and sides to the other person requires that those sides be identified. Thus, a spatial framework is redundant.

### **Spatial Transparency and Representation of Depictions**

Although mental frames are under strategic control, subjects demonstrated different preferences for models and diagrams. In memory, narrative descriptions and 3D models spontaneously led subjects to adopt the internal perspective and create spatial frameworks, whereas diagrams spontaneously led subjects to adopt the external perspective. Thus, something about the kind of depiction influences what perspective a person will take. The essential difference between models and diagrams is their relative degrees of "spatial transparency." By this I mean the directness with which 3D information is available to the viewer. Depictions that directly convey 3D information are transparent and lend themselves to the internal perspective. This is because the depiction makes it relatively easy to mentally construct a 3D representation of the scene and place oneself in it. Depictions that convey 3D information in an abstract fashion and are not very transparent are easier to think of from an external perspective.

Models are highly transparent because they have a 3D structure directly corresponding to that of the scene. It differs in scale, which is not crucial to the direction task employed. Narratives, interestingly, are also fairly transparent, despite not being a physical medium at all. Narratives make use of spatial language that taps a rich 3D conceptualization of space, making it easy to build a 3D mental model from the internal perspective. Diagrams, like the ones used in this research, are 2D and schematic. An oblique line was used to convey depth, which does not correspond directly to physical or perceived space. The flatness of the diagrams presumably encouraged subjects to take the external perspective and treat the character and objects in the diagram as a whole pattern to be analysed.

Two recent experiments explored the notion of spatial transparency. The goal of the first was to find out whether pictorial depth cues, which convey the third dimension in graphics, lead the viewer to spontaneously create spatial frameworks of scenes. Pictorial cues can be strong indicators of depth and should make a diagram a more direct depiction of all three dimensions. These cues were lacking in the original, symbolic diagrams, and that could have suggested an external perspective to subjects. Having easy access to all three dimensions may be the key to using the spatial framework strategy.

In one experiment systematically varied the cues to depth in diagrams. In the Standard Condition, subjects viewed the diagrams used in previous experiments. Thus, no depth cues were present. In the Intermediate Condition, the person was placed in a room frame that has cue of converging lines. The side and back walls were colored in gray tone to make them appear solid. The person was shown on a bench to indicate realistically the need for support due to gravity. The relative size of labels was manipulated to also indicate depth. This kind of diagram is still abstract and relies on symbols. In the Perspective Drawing Condition, subjects viewed hand rendered drawings without symbols. The person was shown on a bench to indicate the need for support from gravity. No axes were drawn in the diagram. Objects were placed along virtual axes. Objects were indicated by actual drawings rather than labels to increase the realism of the diagrams. The diagrams used converging lines, relative size, texture gradient, and shadows to convey depth.

Subjects learned four critical scenes in each condition. Subjects were allowed to study the diagram for as long as they wished, then returned it to the experimenter. Subjects responded to direction probes from memory as in previous experiments. The orientation of the person in the scene was varied as before.

The data are shown in Table 9. The pattern of response times in the standard condition conformed to the intrinsic computation pattern. Critically, subjects were faster to head/feet than front/back than left/right at all orientations. This replicates previous experiments. Response times in the intermediate and perspective conditions conform to predictions of the spatial framework analysis. Critically, subjects were faster to head/feet than front/back for the upright and upsidedown orientations, but faster to front/back than head/feet for the reclining orientations. Despite the limited depth information of the intermediate diagrams, subjects spontaneously adopted the internal perspective of the person. There appears to have been enough direct information about all three dimensions for subjects to create 3D mental models of scenes. That subjects adopted the internal perspective for the perspective drawings is consistent with the hypothesis that spatial transparency governs the selection of a mental frame for diagrams.

Table 9  
Mean response times (in seconds) to direction probes for standard, intermediate, and perspective diagrams

Posture	Direction					
	Head	Feet	Front	Back	Left	Right
STANDARD DIAGRAMS						
Upright Mean	3.386 3.367	3.348	3.552 3.671	3.790	4.666 4.743	4.820
Upside down Mean	3.648 3.694	3.739	3.893 4.014	4.134	5.987 6.011	6.035
Reclining to left Mean	3.699 3.704	3.709	3.860 4.001	4.142	4.684 4.672	4.660
Reclining to right Mean	3.728 3.739	3.750	3.947 4.046	4.144	4.927 4.772	4.618
INTERMEDIATE DIAGRAMS						
Upright Mean	3.607 3.576	3.545	3.750 3.882	4.014	4.121 4.176	4.230
Upside down Mean	3.873 3.829	3.785	4.127 4.212	4.298	5.102 5.129	5.156
Reclining to left Mean	4.226 4.263	4.300	3.965 3.948	3.932	4.644 4.666	4.688
Reclining to right Mean	4.146 4.068	3.989	3.896 3.891	3.886	4.376 4.334	4.292
PERSPECTIVE DIAGRAMS						
Upright Mean	3.432 3.388	3.344	3.721 3.791	3.861	4.113 4.152	4.191
Upside down Mean	3.773 3.814	3.855	4.309 4.301	4.293	6.519 5.916	5.314
Reclining to left Mean	4.032 4.076	4.120	3.690 3.658	3.625	4.781 4.701	4.621
Reclining to right Mean	4.120 4.084	4.048	3.706 3.712	3.719	4.673 4.560	4.446

A second experiment further examined the effect of spatial transparency. This experiment determined whether subjects would employ intrinsic computation for model scenes if depth cues in the model were reduced, rendering the model closer to a diagram. Subjects learned scenes portrayed by a physical model. The model was the same as used in previous experiments. Subjects learned scenes under two viewing conditions. The same procedure was followed in both viewing conditions. In the normal viewing condition, subjects sat about two feet from the model with their chair was adjusted in height so that Homer was at eye level. The model was presented in normal room light. In the impoverished viewing condition, subjects wore an eyepatch over their non-preferred eye to eliminate binocular cues to depth. Subjects sat about two feet from the model, with Homer at eye level. The model was placed in a black hemispherical cardboard enclosure and subjects viewed the model through a circular opening. Thus, the model was not seen in any environmental context. The model was illuminate by a single light from directly above.

The pattern of response times (see Table 10) in the standard condition conformed to the spatial framework pattern, replicating previous experiments. Response times in the impoverished condition conformed to predictions of the intrinsic computation analysis. Critically, subjects were faster to head/feet than front/back than left/right at all orientations. Thus, when a model is viewed under conditions that reduce depth cues, subjects treat it like a flat diagram and employ an external perspective. These results further support the hypothesis that the amount of 3D information available in the depiction guides viewers' selection of a mental perspective to represent the depicted scene.

In both experiments, there were no overall differences in response times between conditions. Subjects were just as fast to standard, intermediate, and perspective diagrams, and to normal and impoverished viewing conditions of a model. Thus, it is not that any one perspective is necessarily better for the basic localization task. The basic task, however, is an abstract lab test and doesn't capture the complexities of real-world tasks in which people make spatial judgments. It is possible that a particular strategy is better than the other in certain situations, and which is better depends on the nature of the setting and task demands confronting a person. This is an area in need of further research.

Table 10  
Mean response times (in seconds) to direction probes for standard and impoverished viewing conditions of model scenes

Posture	Direction					
	Head	Feet	Front	Back	Left	Right
<b>STANDARD</b>						
Upright	3.438	3.379	3.702	3.862	3.903	4.275
Mean	3.408		3.782		4.089	
Upside down	3.745	3.855	4.239	4.207	6.657	5.406
Mean	3.800		4.223		6.032	
Reclining to left	4.075	4.112	3.792	3.771	4.753	4.652
Mean	4.094		3.782		4.702	
Reclining to right	4.098	4.087	3.797	3.675	4.564	4.536
Mean	4.092		3.736		4.550	
<b>IMPOVERISHED</b>						
Upright	3.314	3.223	3.504	3.711	3.972	3.849
Mean	3.268		3.608		3.910	
Upside down	3.611	3.490	3.982	4.085	4.900	5.004
Mean	3.550		4.034		4.952	
Reclining to left	3.642	3.609	3.890	3.868	4.439	4.284
Mean	3.626		3.879		4.362	
Reclining to right	3.533	3.469	3.644	3.704	4.092	4.161
Mean	3.501		3.674		4.142	

### Body Asymmetry and Accessibility in Spatial Frameworks

Spatial frameworks are well-established phenomena, but a number of issues remain unresolved. The spatial framework analysis predicts accessibility largely on the basis of asymmetries of body axes. Asymmetries are assumed to affect the salience or usefulness of a body axis for coding location in a mental model. The nature of the relationship between asymmetry and retrieval, however, has not been clearly established. One project addressed how asymmetry of body axes influences accessibility of location within a spatial framework.

There are at least two theoretical stances that could predict the spatial framework pattern of

accessibility. The first can be termed the *Salience Account*. According to this hypothesis, information in a mental model is activated in working memory on the basis of its salience/relevance in the described situation. This model is largely derived from Morrow and Greenspan's (1989) analysis of accessibility of information in mental models. In a mental model, some objects and relations are more prominent than others. That is, they are more likely to be needed, and are more relevant to understanding the situation. Thus, mental models establish priority or salience gradients and adjust retrievability of objects and relations according to their relative salience value.

Salience is partially determined by focus in the narrative itself, but more so by schematic knowledge of that class of situation. It informs the reader of the extent to which particular objects and spatial relations are relevant to the situation. Salience is transformed into accessibility by a process of foregrounding, whereby information in a mental model is activated in working memory. Because limited levels of information can be maintained (see Baddeley, 1990), levels of activity of objects and their spatial relations are set by their salience. More salient entities receive greater activation (are more foregrounded) than entities of lesser salience (which consequently consume fewer resources of working memory).

The spatial framework analysis describes an a priori salience gradient of the body axes for upright and reclining postures. Here, salience is determined by the physical features of body axes that make the axes useful for localizing objects. Relatively strong asymmetries of a body axis make that axis an important feature of the egocentric situation. According to the *Salience Account*, asymmetry affects the relative importance of the body axes to the reader's conceptualization of a described scene. Thus, the more asymmetric the axis, the more salient it is. The more salient a relation is, the more foregrounded it is in the reader's spatial framework, and hence the more accessible. In the case of the head/feet axis, its relation to gravity, which also affects the importance of spatial relations, also determines that axis' salience.

A second model is the *Direction Decision Account*. Historically, the difficulty of identifying directional relations, especially left versus right, has been linked to difficulty in discriminating direction poles of axes, verbal labels for directions, or body cues to direction. Numerous studies have demonstrated that the speed of judging relative direction depends on the axis of judgment (e.g., Farrell, 1979; Loftus, 1978; Maki, Grandy, & Hauge, 1979; Sholl & Egeth, 1981). Left and right judgments are particularly difficult. Maki et al. (1979) argued that discriminating directions along an axis is a problem of labelling. In their formulation, left/right information is as perceptually salient as above/below or front/back, but the meanings of left and right are more difficult to access and process. This may result from learning left and right terms in the context of few clear indicators of those directions (Corballis & Beale, 1976). Evidence for a labelling effect comes from findings that people are slower to make left/right judgments when verbal labels are used to identify direction but not when abstract symbols are used (Maki et al., 1979; Sholl & Egeth, 1981). Bryant (in press) has also found that people have equal access to all directions when visually orienting to locations rather than making explicit directional responses.

On this basis, the *Direction Decision Account* argues that assessing a particular body direction in the spatial framework paradigm involves discriminating one pole of a body axis from the other. For example, to say what is to one's left, an implicit decision is made as to which pole of the left/right axis corresponds to that direction. Similarly, one distinguishes head from feet and front from back before localizing an object. The difficulty of the decision depends on cues that uniquely distinguish one pole from the other. Cues are related to the asymmetric structure of the body axes. Head/feet and front/back have strong physical, perceptual, and behavioral asymmetries



that differentiate the head from feet and front from back. The left/right axis has few asymmetries to specify which direction is which.

In this account, the spatial framework analysis describes the relative presence of cues useful in making direction decisions. For an upright person, head and feet are easier to discriminate than front and back because the head/feet axis has strong physical asymmetries and is correlated to an environmental axis that also provides cues to direction. Left and right are the hardest directions to discriminate. Assuming response time to access direction is a function of the difficulty of the discriminative decision, this account predicts that people will be faster to access head/feet than front/back than left/right relations. When the person reclines, the head/feet axis is no longer associated with gravity and the stronger asymmetries of front/back predominate.

This project, comprising W. Geoffrey Wright's Masters degree, distinguished the two theories and determined what role asymmetry plays in producing the spatial framework pattern. The two theoretical views can be distinguished empirically by contrasting their predictions of accessibility when subjects identify specific directions at which objects are located (front, back, head, feet, left, and right) versus the body axis along which an object is located (front/back, head/feet, or left/right). The Direction Decision Account claims that differential accessibility results when a person discriminates directions along a body axis. The axes themselves are not assumed to differ in accessibility. If judging simply the axis with which an object is associated, no direction decision is necessary, and subjects should respond equally fast to all axes. When identifying individual directions, the spatial framework pattern of response times is expected because subjects distinguish directions along a body axis. The Salience Account claims that differential accessibility results from foregrounding of locations based on the salience of the body axes with which they are associated. Salience will exist regardless of how the directions or body axes are accessed. The Salience Account predicts the spatial framework pattern of response times in both cases because the salience of body axes determines accessibility of locations.

The spatial framework analysis has been replicated when subjects were probed with the names of objects and responded by indicating its direction (Bryant & Tversky, 1992). Capitalizing on this finding, subjects read narratives that described the prototypic situation with "you" the reader inside an array of objects at the six body sides. After reading the first part of the narrative, subjects turned to a computer and continued reading. The narrative continued to describe "you" in the scene, indicating that you turned to face different objects and/or changed posture (upright or reclining). During this phase, subjects responded to "object probes." The name of an object appeared on the screen and subjects indicated its location. Two kinds of responses were collected. For half the narratives, subjects responded to probes by naming the specific direction at which the object was located. For the other half, they will responded by naming the body axis (left/right, front/back, or head/feet) along which the object was located. Responding with the axis of an object relieves the subject of the need to distinguish between the directional poles of that axis. If the spatial framework effect results from difficulty in differentiating the two poles of an axis at the time of access, the general spatial framework effect should not be evident when subject access only axes rather than individual directions. If the axes themselves convey differential accessibility, the spatial framework pattern should emerge regardless of whether subjects access directions or axes.

The data are shown in Table 11. Subjects in the direction decision task exhibited the spatial framework pattern, being faster to head/feet than front/back than left/right for the upright posture, and faster to front/back than head/feet than left/right for the reclining posture. The overall response times and patterns of response times were the same for the axis task. The spatial framework

pattern was present in the axis task condition even though subjects did not have to distinguish the poles of body axes. Even when it is unnecessary to discriminate directional poles, above/below relations are more accessible than front/back relations which are more accessible than left/right relations. This finding contradicts predictions of the Direction Decision account. Differences in response times to retrieve objects along different axes cannot be attributed to differences in the time necessary to discriminate directional poles.

Table 11  
Mean response times (in seconds) to direction versus axis probes in memory for narratives

Posture	Direction					
	Head	Feet	Front	Back	Left	Right
Upright	1.66	1.78	1.66	2.41	2.91	2.52
Mean	1.73		2.06		2.74	
Reclining	2.56	2.25	1.81	2.51	3.01	3.07
Mean	2.37		2.17		3.07	

Posture	Axis		
	Head/Feet	Front/Back	Left/Right
Upright	1.62	1.97	2.24
Reclining	2.23	2.04	2.64

An unexpected interaction between task conditions occurred. The degree to which subjects were slowest to left/right was greater in the direction than axis task condition. In contrast, response times to front/back and head/feet were basically the same in the two conditions. Although the interaction effect was significant for only the upright posture, it still gives rise to questions about differences in the processes used for making spatial judgements. A possible interpretation is that, unlike head/feet or front/back, accessing left/right may involve distinguishing directional poles.

Overall, the Salience Account was supported and axes are differentially important to one's mental representation of space. The head/feet and front/back axes derive their salience from asymmetries present in body morphology, perception, and behavior, and environmental cues. The left/right axis, however, is virtually bereft of asymmetries and cues. This disparity in salience may lead people to use a decision process to aid left/right localization but not front/back or head/feet localization. In the absence of strong body asymmetries or environmental cues along the left/right

axis, one has to resort to a decision process in determining left from right.

A second goal was to investigate the kinds of asymmetries that play a role in structuring spatial frameworks. The spatial framework analysis concentrates on physical asymmetries of the body. There is, however, a long history of studying *functional asymmetry* or lateralization of the body and its potential cerebral underpinnings (e.g., Hellige et al., 1994; Hopkins, Bard, Jones, & Bales, 1994; White, Lucas, Richards, & Purves, 1994). Laterality is generally expressed as a preference to use the left or right side of the body to perform tasks. The spatial framework implies that some kinds of functional asymmetries, such as the orientation of perceptual systems frontward, determine accessibility of locations. It is not clear, however, whether lateralization of the left/right axis plays a role in determining the accessibility of left and right directions. In particular, the present research considers whether the degree of lateralization attenuates the spatial framework pattern of accessibility. A second experiment determined whether left/right directions are more accessible relative to front/back and head/feet directions for strongly lateralized than weakly lateralized individuals. The results of this experiment will help determine the kinds of asymmetries that determine accessibility in spatial frameworks. In particular, they address the question of whether only enduring physical and perceptual asymmetries, like those that mark the head/feet and front/back axes, contribute to the accessibility of objects. The alternative is that individual asymmetries of functional preference affect the development of spatial frameworks and accessibility of information within them.

We screened participants for their functional laterality using the Edinburgh Handedness Inventory (Oldfield, 1971) and the Preference Inventory for handedness, footedness, eyedness, and earedness (Coren, 1993). Participants scoring in the 90th percentile for hand preference and showed the same preference in at least three categories (eye, ear, hand, or foot) on the Preference Inventory were classified as highly lateral. Those below the 30th percentile on the Edinburgh Handedness Inventory and with consistent preference in less than three categories on the Preference Inventory were classified as alateral. Due to the rarity of strongly left lateralized individuals, only right lateralized individuals were included in the highly lateralized group.

Subjects read narratives like those in the first experiment and were similarly probed for the locations of objects. Only the direction task was used in this experiment. Response times of the alateral group should correspond to the spatial framework pattern. For the strong lateralized group, the functional asymmetry may make the left/right axis very salient. If so, we would expect subjects to show equal response times to left/right and front/back, or a reliably smaller difference than exhibited by the alateral group. Alternatively, functional asymmetry may not contribute to the use of spatial concepts. In this case, both groups should show the spatial framework pattern and same response time differences between front/back and left/right.

The results are shown in Table 12. The alateral group was somewhat faster overall than the highly lateral group. The spatial framework pattern was evident in both groups, with subjects being faster to head/feet than front/back than left/right for the upright posture, but faster to front/back than head/feet than left/right for the reclining posture. Most importantly, the degree of functional laterality did not affect the *size* of the difference between response times to left/right and the other two dimensions. There was no interaction of laterality with probed direction.

Table 12

Mean response times (in seconds) to direction probes for strongly lateral and alateral groups

Posture	Direction					
	Head	Feet	Front	Back	Left	Right
<b>HIGHLY RIGHT LATERAL GROUP</b>						
Upright	1.52	1.72	1.60	1.97	2.38	2.26
Mean	1.62		1.78		2.32	
Reclining	2.02	1.97	1.57	2.11	2.71	2.46
Mean	1.99		1.84		2.59	
<b>ALATERAL GROUP</b>						
Upright	1.48	1.57	1.59	1.82	2.12	1.99
Mean	1.52		1.70		2.06	
Reclining	1.86	1.84	1.54	2.01	2.17	2.18
Mean	1.85		1.77		2.17	

These results indicate that functional asymmetry is not a salient feature in a spatial framework. Readers do not seem to assign salience to left or right on the basis of any lateral preference they might possess. This suggests that only enduring, universal asymmetries are salient in spatial frameworks. Universal asymmetries consist of the gross morphological differences between one's front and back, and between one's top and bottom, as well as the perceptual differences that arise from the orientation of perceptual mechanisms frontward. These asymmetries exist for all people, which presumably is what makes them so important.

### The Internalization of Geometric Principles Through Evolution

In addition to the research on spatial frameworks, I conducted with graduate student Margaret Lanca studies on the metric nature of spatial representations. The immediate goal was to learn the extent to which geometric principles are preserved in spatial representations. The ultimate goal is to learn how metric knowledge can be incorporated with the sorts of categorical spatial representations exemplified by spatial frameworks.

An increasingly influential perspective in psychology is that evolution has shaped the cognitive mechanisms that guide behavior. For example, evolution seems to have equipped humans with some innate spatial knowledge about the Euclidean geometric principles that describe the local terrestrial environment. To understand human spatial knowledge, we need to investigate the geometric level of spatial representation. Some studies have shown that people possess good

spatial skills that seem to preserve the Euclidean properties of the objective world. Other studies, however, have demonstrated systematic distortions of spatial judgments, leading to suggestions that spatial representations are based on some non-Euclidean metric.

In one relevant study, Brambring (1976) presented subjects with a series of tactile figures comprised of two sides of a right triangle. Blind and blindfolded sighted adults felt the horizontal and vertical sides with a finger then estimated the triangle's hypotenuse length. Subjects systematically underestimated the true hypotenuse lengths. Moreover, when Brambring solved for  $r$  in the Minkowski  $r$  metric (a general description of metric geometries), he found the mean  $r$  exponent for all subjects was significantly less than 2 (the  $r$  value that characterizes Euclidean geometry). Brambring concluded that people's spatial representations derived from touch did not preserve Euclidean properties of space but were based on a city-block metric.

Before accepting this conclusion, however, we should consider the stages of processing necessary to perform the spatial task. Subjects must first perceive some parts of a spatial configuration, then create a mental representation and compute spatial relations not directly perceived, and finally execute a response. Errors, systematic or otherwise, can occur during any of these three stages. Subjective perception of quantities such as haptic length, for example, are typically a nonveridical power function of the objective physical quantity (Stevens, 1957). Brambring (1976) failed to distinguish distortion in hypotenuse estimation due to misperception of triangle components from distortion in the metric structure of the representation itself. If subjects misperceived the component lengths they would be expected to distort the hypotenuse relative to its true length, even if their representation itself conformed to Euclidean geometry.

The primary goal of our study was to examine whether people's representations of simple spatial configurations learned by touch conform to the principles of an internalized Euclidean geometry. To do this, we distinguished between errors in spatial performance caused by perception versus distortions in the underlying representation itself. Our hypothesis was that when errors in perception were taken into account, people's spatial inferences would obey rules of Euclidean geometry, such as the Pythagorean theorem for calculating triangle hypotenuse length.

*Procedure and Results.* Subjects in all experiments were young adult students with no history of visual impairment. Subjects were blindfolded during the experiments. In Experiments 1 and 2, subjects felt vertically and horizontally oriented raised lines, then reproduced the line lengths by tracing along a test line. Haptic perception of line length was a non-veridical power function of true length (exponent = .87). Subjects tended to underestimate length and underestimations became greater with longer lines. In Experiments 3 and 4, subjects felt vertical and horizontal sides of raised right-triangles, then estimated the two side lengths and inferred the hypotenuse length. Subjects' hypotenuse estimates were predictable from their subjective estimates of the two component sides using the Pythagorean Theorem, but only when subjects employed a visual imagery strategy during encoding. Minkowski  $r$  values were derived for subjects' subjective triangles. For subjects using imagery, the mean  $r$  value (2.10) was not significantly different than the Euclidean 2. For subjects using other strategies (e.g., counting units of distance or time while feeling lines), the mean  $r$  value (2.88) was significantly greater than 2. Experiment 4 also indicated that instructions to use imagery have little impact on the strategies actually employed and that triangles with unequal sides are more difficult to represent in an Euclidean metric. Contrary to Brambring (1976), errors in inferring the hypotenuses of triangles from touch seem largely attributable to misperception of spatial components rather than the underlying representation metric.

People can form spatial representations that conform to Euclidean axioms, but this ability may rely on the use of visual imagery and may be hampered by configuration complexity.

*Conclusions.* Our examination of the geometric level of spatial knowledge has been based on the theoretical grounds that humans possess representational structures that have, over the course of evolution, internalized the most important invariants of the external world (Shepard, 1982). Among the most important invariants for any terrestrial organism are the Euclidean axioms that describe the nature of space. Indeed, subjects in our study seemed to create mental representations that were isomorphic to physical space.

Yet, if Euclidean metric representation is desirable and adaptive, why are people not perfect at operating in space? Our research, albeit limited to 2-D haptic space, points to at least two reasons. One is that perception of spatial relations is not veridical. We observed for touch that the perception of simple line segments is governed by a nonveridical power function. Errors made during the initial encoding of length necessarily prevent a one-to-one correspondence between internal and external space, even when the internal metric obeys all the geometric principles of external space. A second reason is that people are active interpreters of their situation who devise strategies to learn spatial configurations. Some strategies, such as a counting strategy are less effective than others, such as creating a visuo-spatial image.

Overall, people's representation of space exhibits an impressive attunement to the geometric principles of real space. However, the task of learning a spatial configuration, representing it in memory, and making inferences from it present an equally impressive set of challenges to our spatial knowledge.

### **Memory for Sequences of Spatial Locations**

In research comprising Ilavenil Subbiah's doctoral thesis, we investigated whether spatial locations are stored in memory automatically or effortfully. We examined whether factors such as intentionality, simultaneous processing demands, practice, and the use of learning strategies affect the encoding of spatial location.

Because studies of effortful or automatic encoding processes in human spatial memory are relatively scarce, studies of verbal memory were used as a guide in developing a suitable experimental paradigm. A well-documented effect in verbal memory for a list of words is the primacy effect. This is the elevated recall of the first few items presented in a sequence, resulting from additional rehearsal of these items. Our research employed sequential presentation of spatial locations and the primacy effect to investigate storage and retrieval processes for spatial locations. In our experiments, subjects viewed an array of forty boxes (locations) on a computer screen. Ten of the boxes were marked by a target in a sequential fashion. Memory for locations of the targets was tested after a delay of one minute during which the subject completed a distracting task.

The first experiment found no primacy effect under incidental (in which subjects were not informed of the memory test) or intentional (in which subjects were informed of the memory test) learning conditions. This initially suggested that spatial locations were stored automatically because the lack of an effect of intentionality is a hallmark indicator of automatic processing. However, a concurrent task, which required subjects to move their eyes away from the presentation display, may have interfered with the rehearsal of locations. Disrupting rehearsal would have weakened any rehearsal effects contributing to the primacy effect and removed an opportunity for the primacy effect to occur.

A second experiment used a delayed recall test with no concurrent task during study. This time, a primacy effect was observed in recall of locations, suggesting effortful processing of spatial location. A third experiment examined recall under intentional and incidental learning conditions. During the study phases subjects engaged in a concurrent task that did not require subjects to move their eyes from the spatial display (rating the esthetic appeal of the target in its location). A primacy effect was observed only under intentional learning conditions, when subjects knew of the test and could rehearse its location. These findings, in conjunction with the results of the first experiment, suggest that a primacy effect does occur in memory for spatial location, but that the effect is eliminated when rehearsal is disrupted by eye-movements away from the spatial display. This suggests that eye-movements form a crucial component of the encoding process of spatial information.

Three additional experiments further investigated the role of eye-movements in spatial encoding. One experiment used a concurrent task specifically designed to require subjects to move their eyes to the edge of the display between presentations of targets (naming a color patch presented at one of the four edges of the screen). The primacy effect was eliminated, indicating that eye-movements directly from target location to target location are central to the rehearsal of sequentially presented spatial locations. The next experiment demonstrated that performing a concurrent auditory localization task did not remove the primacy effect. This shows that concurrent processing of abstract spatial information, or spatial information in another sensory domain, does not interfere with rehearsal of visually presented spatial items. This finding confirms that eye-movements, rather than spatial processing at a higher level, play a role in the rehearsal process. In a third experiment, subjects were prevented from making eye-movements by having them fixate their gaze on the center of the computer display. Subjects had to process location by shifting visual attention without shifting their eyes. Because the display was within the field of view and subjects are able to shift attention to non-foveal positions to process information (Klein, Kingstone, & Pontrefact, 1992), subjects potentially had the opportunity to rehearse spatial location. The primacy effect, however, was greatly reduced by this manipulation, confirming that physical eye-movements rather than shifts of visual attention are crucial for rehearsing location.

The final two experiments were designed to determine whether spatial locations were stored as chains of locations linked by eye-movements, or as clusters of locations organized by spatial proximity. One experiment forced a break in the hypothesized chaining process by changing the appearance of the locations in the sequence. The fifth target location turned from a box to a blue circle, which surprised subjects and made this location distinctive. The change captured attention and disrupted the sequence of rehearsals. Recall of the target location immediately following the change was significantly reduced, suggesting that locations are stored as a chain. Altering the stimuli within the sequence affects encoding and disrupts the ability of subjects to link following items to the sequence of earlier ones. A second experiment examined the order of recall of target locations. Subjects recalled locations mostly in the temporal order in which they had been presented, further supporting the chaining hypothesis. In addition, subjects exhibited some tendency to recall proximal locations together, suggesting that subjects employ some spatial clustering as well (see Hirtle & Jonides, 1985).

The findings of this line of research indicate that spatial locations are effortfully rehearsed rather than stored automatically. Rehearsal of spatial locations involves eye-movements between locations. Sequentially presented spatial locations seem to be stored primarily by their temporal order of presentation.

## Pattern Perception

How much can you distort a pattern and still be able to recognize it? The answer to this question, I believe, allows us insight into the processes the mind uses to recognize natural objects. In collaboration with Catherine Reed of the University of Denver, I have begun to study how people process shape and spatial relations within patterns. The goal is to determine what kind of spatial information people perceive in a pattern, and to what extent they are capable of making mental transformations of spatial relations. Participants study a simple pattern, then identify which of two alternatives matches the original figure. The test items are created by manipulating various aspects of the figure; its orientation (it could be rotated  $90^\circ$ ), its scale (it could be expanded or shrunk), or its ratios of distance and angle (it could be stretched into a rectangle). By measuring people's accuracy and speed at matching test items to stimuli, we will be able to determine the extent to which people rely on precise metric information to perceive and remember spatial layouts. Changing the scale and making a square bigger changes distances between points, but doesn't alter the angles. Stretching a square into a rectangle changes both distances and angles. If people can accurately match targets to stimuli in the first case but not the second, this would tell us that people do not need precise distance information to code the layout of figures; they could use ratios of distances. It would also tell us that precise angles or directions are important if people have difficulty when these are altered. By assessing the effect of rotations, we will learn the extent to which people rely on a coding of patterns relative to an external or environmental frame of reference. Overall, this experiment will provide us with insight into the kinds of spatial information people attend to, and their ability to manipulate that knowledge. Prominent theories of object recognition debate the role of "viewpoint invariant" (i.e. geometric) versus "viewpoint dependent" (i.e. frame of reference) information. This research has the potential to help distinguish these theories and clarify the extent to which each type of information is used.

## Spatial Concepts

My research has concentrated on categorical spatial relations because people frequently use words like above and below, and left and right, to describe where things are. But what do these words mean in terms of our understanding of location in space? Objects rarely fall directly on a line from other objects and we need to use spatial terms to describe these relations as well. The question is how well a spatial term applies to a direction in space. A new line of research that I have just started explores the underlying metric structure of spatial categories and explore whether people use prototypes for spatial relations in the same way they use prototypes in other domains. The geometric definitions of spatial terms should be the best examples of those spatial relations, but other directions could be similar to the prototype and be judged to belong to the concept. Thus the "goodness" of a direction as an example of a spatial relation should grow smaller as it deviates more from the prototype.

Major issues in categorization (see Medin & Barsalou, 1987) have been, a) the identification of the structure/nature of the representation of concepts, b) specifying the attributes that are employed in the concept representation, and c) characterizing how categories are used in such tasks as classification, inference, and generation. There are two broad competing classes of theories, but these conflict on very basic issues. *Discrete Category Theories* propose that spatial concepts are defined by strict boundaries that divide space into applicable and non-applicable regions. Most

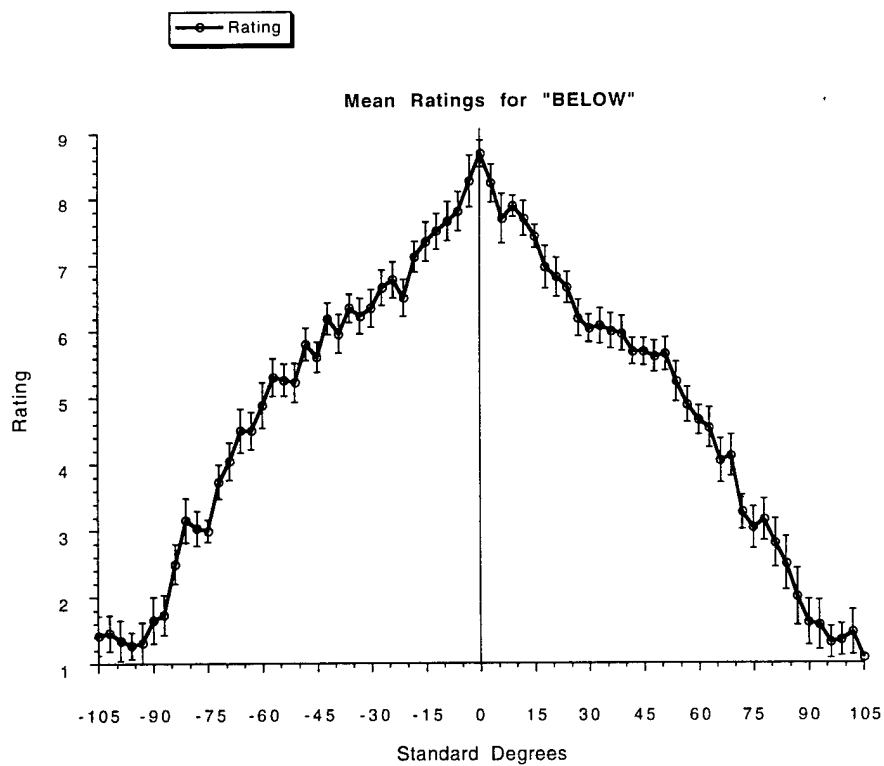
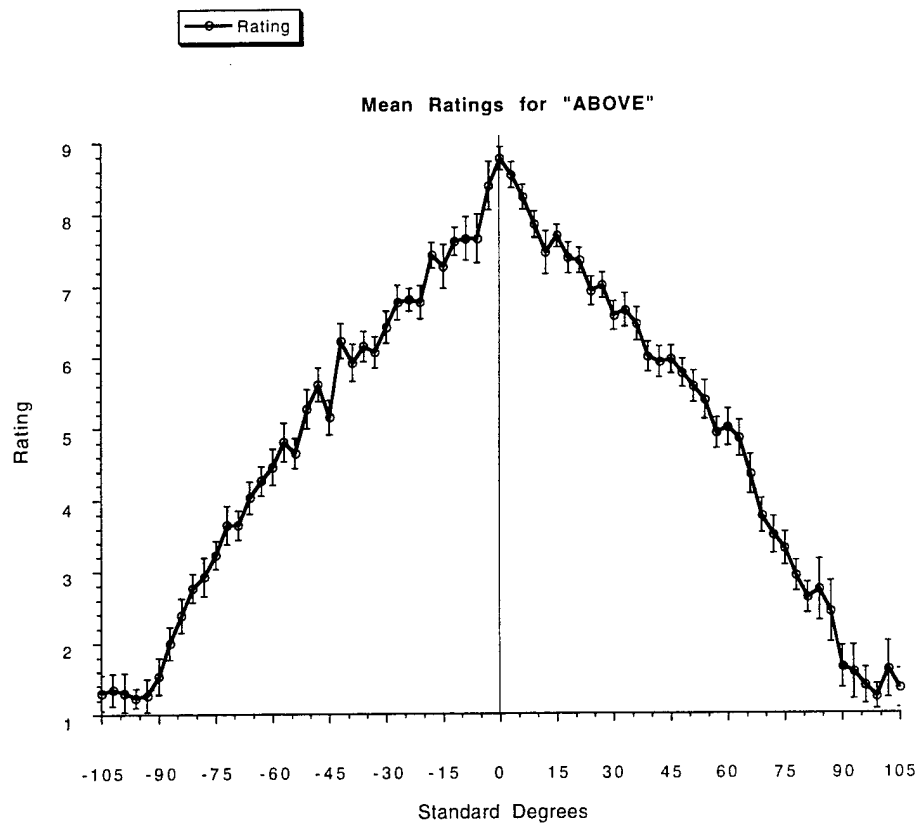


metric information is discarded in representing spatial concepts (see Talmy, 1983). The regions within concept boundaries are all equally valid. Thus, this theory predicts equal applicability of spatial relations over regions of space. *Prototype Theories* (Gapp, 1995; Hayward & Tarr, 1995; Logan & Sadler, 1996) propose that spatial categories are defined by a prototype and a similarity space that relates spatial positions to the prototype along relevant dimensions. The prototype comprises the best example of the spatial relation, specifying the direction and distance that defines the spatial relation. Other relations are related to this prototype by their degree of similarity to the parameters of the prototype. The degree of similarity is a continuous function of the continuous spatial dimensions that make up the category parameters.. Spatial categories are thus "fuzzy" because there are no exclusive boundaries that determine regions that belong and do not belong. Membership is determined by similarity to the prototype, giving the category a graded structure. This theory predicts that the applicability of spatial categories varies continuously over regions of space.

Two experiments systematically applied the theoretical approach used to study natural and perceptual categories. The experiments go beyond simply contrasting theories of categorization by examining very fine discriminations of position to determine how metric information is used to categorize spatial relations. Examining how precisely metric information is used to structure concepts will illuminate whether the internal structure of spatial concepts is continuous or based on a broad division of space into regions of applicability (cf. Logan & Sadler, 1996).

The first experiment assessed people's ability to discriminate the "goodness" of positions as examples of direction concepts. The experiment examined four direction concepts: above, below, left, and right. Subjects viewed stimuli consisting of a square (referent object) with a dot located around it. The position of the dot was varied in  $3^\circ$  increments around the square, but at a constant distance from the square. Subjects rated how well a spatial relation applied to the position of the dot, using a 9-point scale (1 being not applicable and 9 being completely applicable). Subjects made ratings for items relative to one concept at a time. Dot position were randomized across trials. By varying positions in small increments, it was possible to determine whether continuous metric angle forms the basis of concept structure.

Subjects' mean ratings for the four direction categories are shown in Figures 4a-d. The figures show mean rating plotted against "standard degrees," that indicate position relative to the canonical direction. Thus directly above the center of the square was  $0^\circ$  above, and other stimulus locations were designated as positive or negative increments compared to that origin. Ratings varied linearly with the angular position of the dot. The highest ratings were assigned to the canonical directions. Ratings then decreased steadily with angular deviation from the canonical. Ratings approached non-applicability around  $81-84^\circ$  for each direction. This probably reflects the fact that angle was defined with respect to the center of the square, but subjects compared position to the edge of the square to determine concept boundaries (see Gapp, 1995). The results are consistent with the prototype theory. They indicate an internal structure based on metric angle. The results further indicate that spatial concepts are based on continuous metric information because ratings varied in a smooth, continuous function with angular displacement. People have the ability to make very fine distinctions in applicability, over  $3^\circ$  increments. This is only possible if spatial concepts contain precise, analog spatial information.



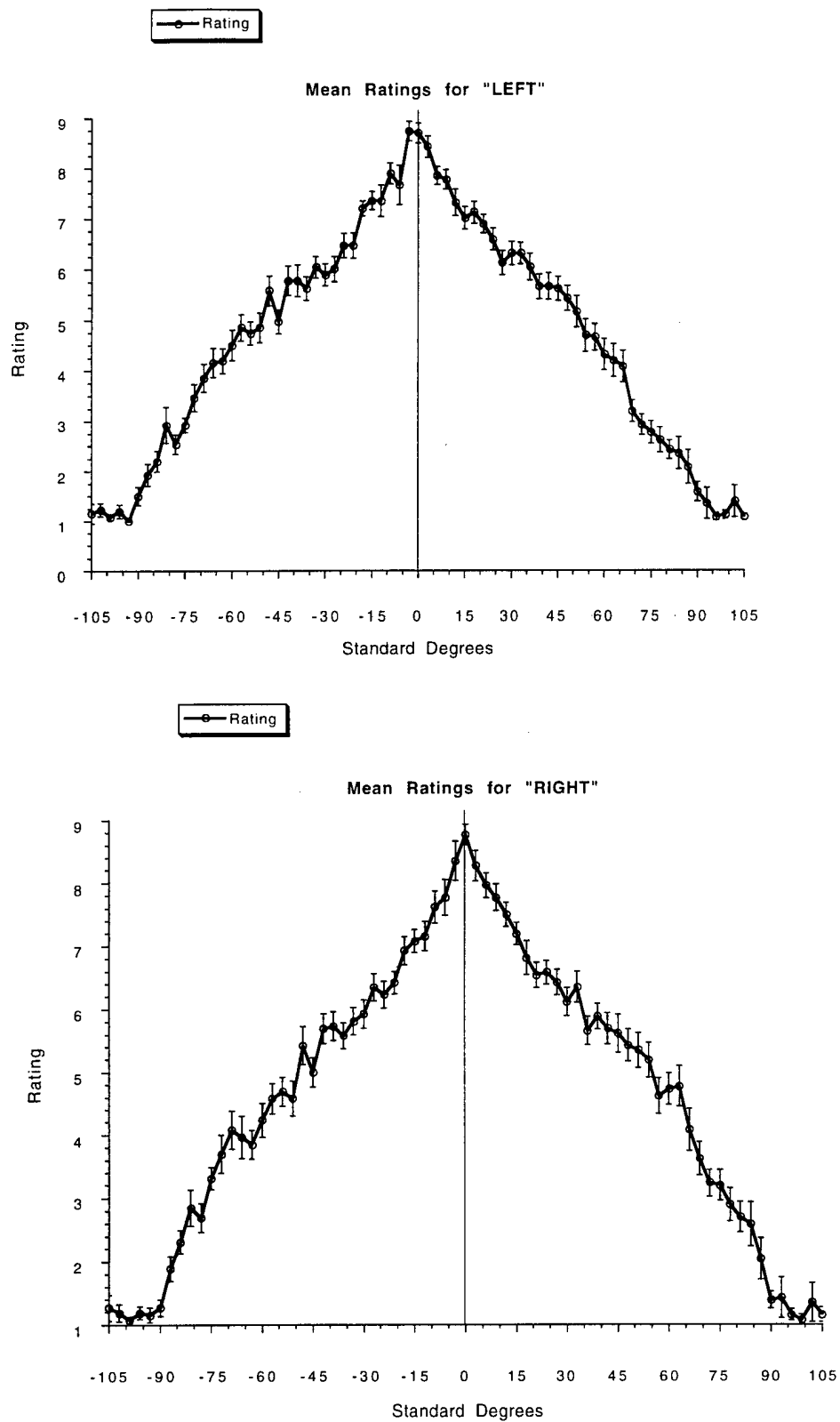
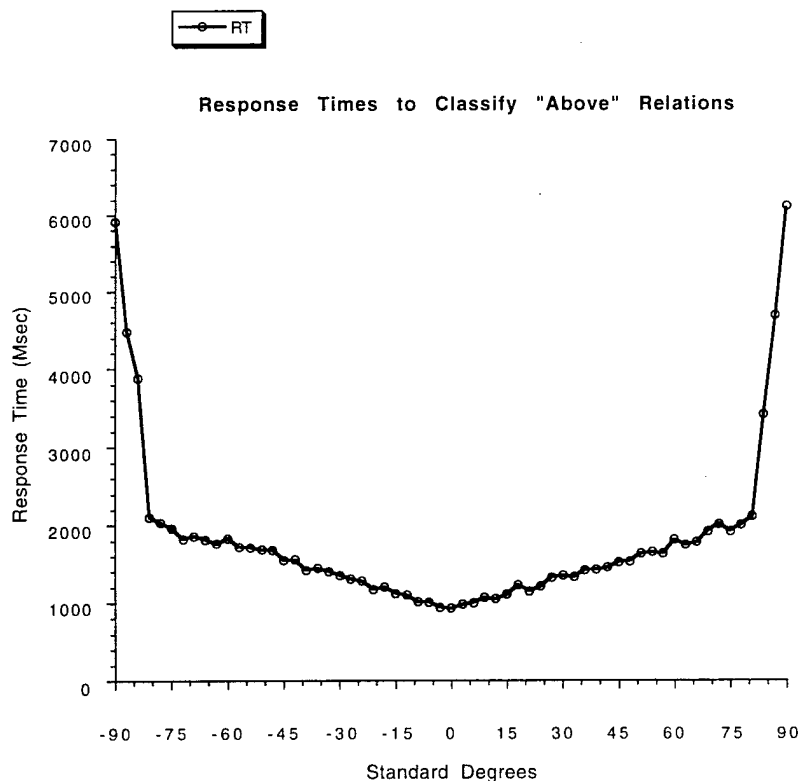
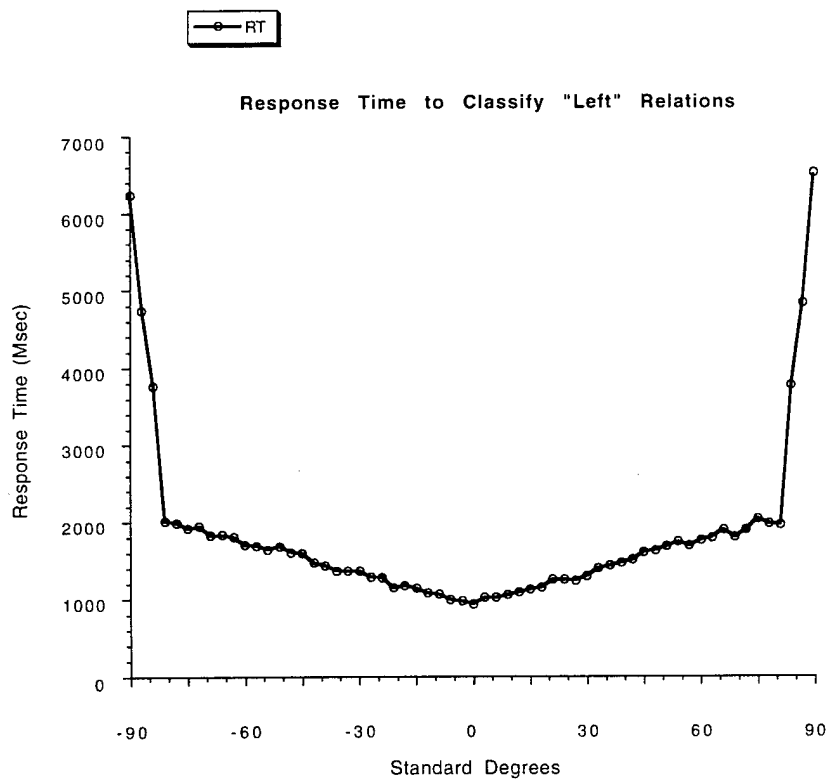
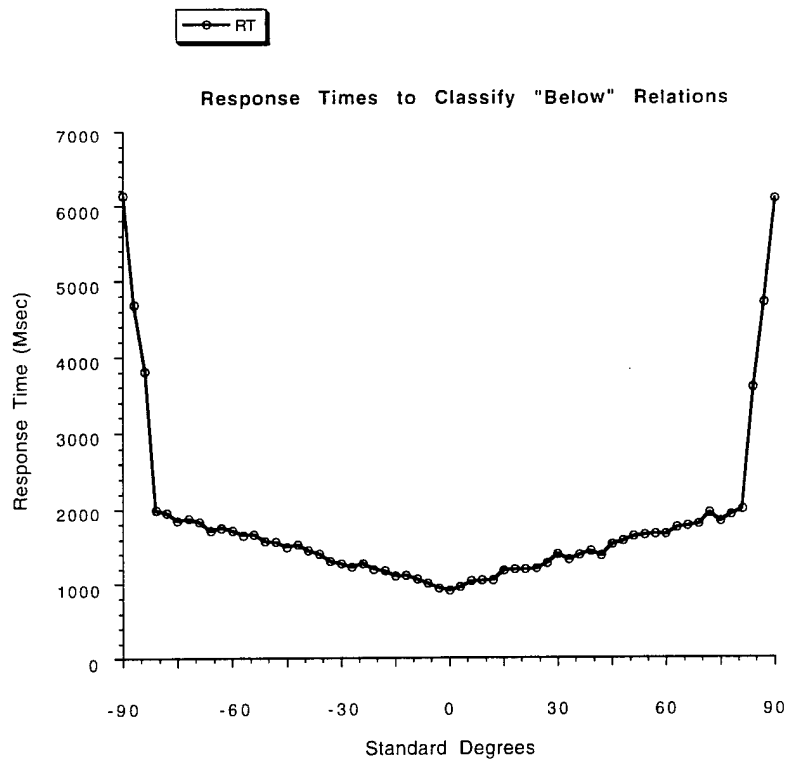


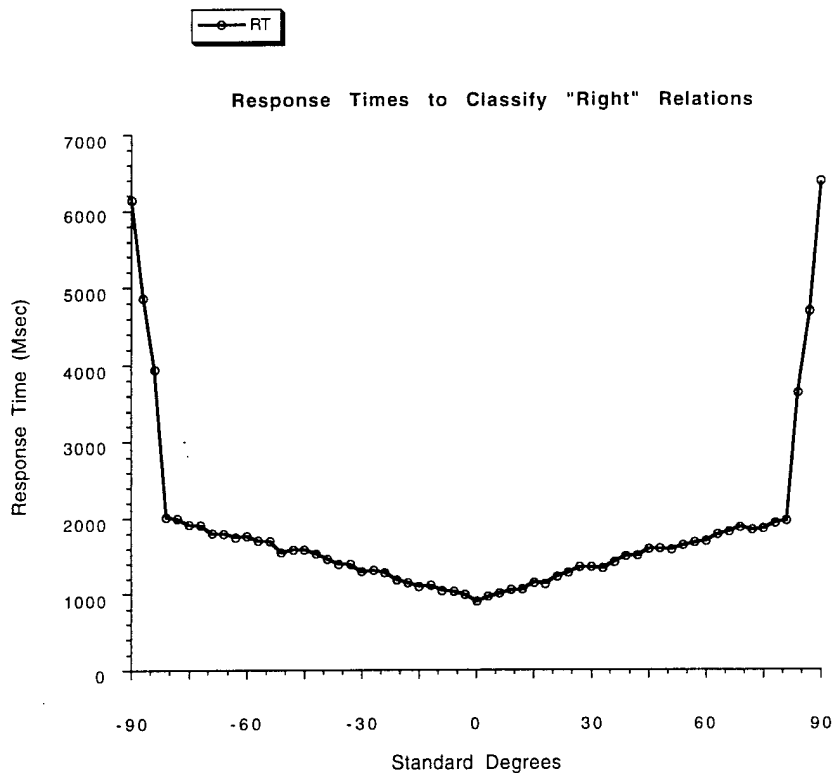
Figure 4a-d. Mean ratings as a function of angular discrepancy from canonical direction

The goodness rating task directly assesses people's perception of concept members, but may reflect demand characteristics because it explicitly asks subjects to think of a concept in terms of gradations of goodness (see Armstrong, Gleitman, & Gleitman, 1983). This might lead subjects to impose structure where none really exists. A second experiment replicated the first using a speeded classification task to assess the functional effectiveness of category members. The same stimuli as the first experiment were used. A direction was indicated on a computer screen, followed by a stimulus with the square (referent) and dot (figure). Subjects indicated as quickly and accurately as possible whether the stimulus applied to that spatial relation. The measure of interest is response time to classify stimuli. This experiment will ensure that observed internal structure does not reflect demand characteristics or a decision process imposed in spatial relations.

Mean response times are plotted against standard degrees in Figures 5a-d. Only response times for correct "yes" decisions are included. Subjects judged stimuli within  $\pm 90^\circ$  to belong to direction categories. The patterns of response times are the same in all four directions, and overall response times did not differ. Consistent with the prototype theory decisions of concept membership depended on angular discrepancy from the canonical direction. Subjects were fastest for the canonical position, and response times increased linearly with angular discrepancy. Response times increased dramatically for stimuli at  $\pm 81^\circ$  and beyond. Thus, stimuli near the boundaries of categories were relatively difficult to classify. The results serve as evidence of internal structure based on continuous spatial properties and that perceiving the spatial relation between two objects is a function of the internal similarity space of the spatial concept.







*Figure 5a-d.* Mean response time to classify positions as a function of angular discrepancy from the canonical direction of direction concepts

This line of research is significant because it can provide an understanding of how people integrate analog metric space with conceptual representation. The research goes beyond previous work that distinguished coarse coding from prototypic theories. It characterizes the internal structure of spatial concepts, how it affects boundaries (division of space into categories), and how it influences perception, memory, and spatial inference.

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## **Participating Professionals**

David J. Bryant, Ph.D., Principal Investigator  
Barbara Tversky, Ph. D.  
William Wright, B.Sc.  
Ilavenil Subbiah, Ph.D.  
Catherine L. Reed, Ph.D.

## **Interactions**

- American Psychological Society, Washington, DC, June, 1994. Dr. Bryant and graduate student Ilavenil Subbiah attended and presented experiments on the use of cognitive strategies to encode spatial location and their effect on patterns of error in spatial memory.
- Psychonomic Society, St. Louis MO, November, 1994. Dr. Bryant and graduate student Margaret Lanca attended and presented experiments demonstrating that people form internally Euclidean representations of triangular configurations from touch.
- University of Denver, March 31, 1995. Dr. Bryant attended and presented experiments demonstrating that people employ highly conceptual spatial frameworks to remember spatial layouts, but perceptual frames of reference when observing layouts. Also presented were findings that indicate that people can employ mental imagery and perception-like processes in memory for diagrams.
- Jean Piaget Society, Berkeley, CA, June, 1995. Dr. Bryant will attend and present experiments demonstrating people's ability to use implicit axioms of Euclidean geometry, and relate this research to an evolutionary perspective on human development.
- International Joint Conference on Artificial Intelligence, Montreal, Canada, August, 1995. Dr. Bryant will attend and present a summary of research on the use of spatial frameworks and intrinsic computation in memory and perception of narratives, observed physical scenes, and diagrams.
- Jean Piaget Society, Berkeley, CA, June, 1995. Dr. Bryant attended and presented experiments demonstrating people's ability to use implicit axioms of Euclidean geometry, and relate this research to an evolutionary perspective on human development.
- International Joint Conference on Artificial Intelligence, Montreal, Canada, August, 1995. Dr. Bryant attended and presented a summary of research on the use of spatial frameworks and intrinsic computation in memory and perception of narratives, observed physical scenes, and diagrams.
- Psychonomic Society, Los Angeles, CA, November, 1995. Drs. Bryant and Subbiah attended

and presented experiments on the use of cognitive strategies to encode spatial location and their effect on patterns of error in spatial memory.

- Psychonomic Society, Los Angeles, CA, November, 1995. Drs. Bryant and Tversky attended and presented experiments demonstrating differences in mental representations of 3D models and diagrams in memory and perception.
- Tufts University, Medford, MA, January 22, 1996. Dr. Bryant attended and presented experiments demonstrating that people can adopt either an internal or external perspective on 3D models and diagrammed scenes.
- AFOSR Vision, Audition, and Perception Workshop, Wright-Patterson AFB, Dayton, OH, June, 1996. Dr. Bryant attended and presented a summary of research on mental perspectives used to understand diagrams and model scenes.
- Eighth Annual Convention of the American Psychological Society, San Francisco, CA, June, 1996. Dr. Bryant and W. G. Wright attended and presented a poster describing two experiments examining the role of body asymmetry in structuring spatial frameworks and mental models of scenes described by narrative.
- 12th European Conference on Artificial Intelligence (ECAI-96), Budapest, Hungary, 1996. Dr. Bryant attended and participated in a workshop on spatial language and understanding. Dr. Bryant presented research on the use of mental frames to understand location in diagrammed scenes.
- University of Massachusetts at Amherst, October 22, 1996. Dr. Bryant presented experiments demonstrating that people can adopt either an internal or external perspective on 3D models and diagrammed scenes.
- 38th annual Meeting of the Psychonomic Society, Chicago, IL, November, 1996. Drs. Bryant, Reed, and Lanca attended and presented two experiments examining the use of intrinsic geometric and egocentric reference frame information for the recognition of patterns.
- GTE Laboratories, Waltham, MA, December, 1996. Dr. Bryant presented research on the mental representation of space in narratives, diagrams, and models.

### **Publications and Publications in Progress**

- Bryant, D. J. (1993). Frames of reference in the spatial representation system. *Behavioral and Brain Sciences*, 16, 241-242.
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### **Papers, Posters, Talks Delivered at Professional Meetings**

Bryant, D. J., *Are mental spatial frameworks used to guide search for objects in observed scenes?* Invited speech, Man-Vehicle Laboratory, Massachusetts Institute of Technology, September, 1993.

Subbiah, I., & Bryant, D. J., *Is there a primacy effect in memory for spatial location?* Poster presented at the Fifth Annual Convention of the American Psychological Society, Chicago IL, June, 1993.

Bryant, D. J., Tversky, B., Lanca, M., & Narasimhan, B., *Mental spatial models guide search of observed spatial arrays.* Poster presented at the 34th Annual Meeting of the Psychonomic Society, Washington, DC, November, 1993.

Subbiah, I., & Bryant, D. J., *Strategies for encoding spatial location.* Poster presented at the Sixth Annual Convention of the American Psychological Society, Washington, DC, June, 1994.

Lanca, M., & Bryant, D. J., *The internal geometry of haptic space.* Poster presented at the 36th Annual Meeting of the Psychonomic Society, St. Louis, MO, November, 1994.

Bryant, D. J., *Reflections of the world in human spatial concepts.* Colloquium. University of Denver, March 31, 1995.

Bryant, D. J., & Lanca, M., *The internalization of geometric principles through evolution.* Poster presented at the 25th Annual Symposium of the Jean Piaget Society, Berkeley, CA, June, 1995.

Bryant, D. J., *Human spatial concepts reflect regularities of the physical world and human body.* Paper presented at the 14th International Joint Conference on Artificial Intelligence, Montreal, Canada, August, 1995.

Subbiah, I., & Bryant, D. J., *Rehearsal and the primacy effect in memory for spatial location.* Poster presented at the 37th Annual Meeting of the Psychonomic Society, Los Angeles, CA, November, 1995.

Bryant, D. J., & Tversky, B., *Acquiring spatial relations from models and diagrams.* Paper presented at the 37th Annual Meeting of the Psychonomic Society, Los Angeles, CA, November, 1995.

- Bryant, D. J., *Regularities of the physical world and human body in spatial cognition*. Invited talk. Tufts University, January 22, 1996.
- Bryant, D. J., *Mental Frames for conceiving of space in diagrams and models*. Paper presented at the AFOSR Vision, Audition, and Perception Workshop, Wright-Patterson AFB, Dayton, OH, June, 1996.
- Wright, W., & Bryant, D. J., *Spatial framework: Differential accessibility of bodily dimensions and effects of lateralization*, Poster presented at the Eighth Annual Convention of the American Psychological Society, San Francisco, CA, June, 1996.
- Bryant, D. J., *Mental frames for interpreting direction terms*. Paper presented at the 12th European Conference on Artificial Intelligence (ECAI-96), Budapest, Hungary, 1996.
- Bryant, D. J., *Representing spatial relations in narratives, models, and diagrams*. Invited talk. University of Massachusetts at Amherst, October 22, 1996.
- Bryant, D. J., Reed, C. L., & Lanca, M., *Frames of reference for form perception in vision and touch*. Poster presented at the 38th annual Meeting of the Psychonomic Society, Chicago, IL, November, 1996.
- Bryant, D. J., *Understanding spatial relations in diagrams and models*. Invited speech. GTE Laboratories, Waltham, MA, December, 1996.